

THE ECOLOGY OF STAR CLUSTERS AND INTERMEDIATE-MASS
BLACK HOLES IN THE GALACTIC BULGESIMON F. PORTEGIES ZWART,^{1,2} HOLGER BAUMGARDT,³ STEPHEN L. W. McMILLAN,⁴
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ABSTRACT

We simulate the inner 100 pc of the Milky Way to study the formation and evolution of the population of star clusters and intermediate-mass black holes (IMBHs). For this study we perform extensive direct N -body simulations of the star clusters that reside in the bulge, and of the inner few tenth of parsecs of the supermassive black hole in the Galactic center. In our N -body simulations the dynamical friction of the star cluster in the tidal field of the bulge are taken into account via semianalytic solutions. The N -body calculations are used to calibrate a semianalytic model of the formation and evolution of the bulge. We find that $\sim 10\%$ of the clusters born within ~ 100 pc of the Galactic center undergo core collapse during their inward migration and form IMBHs via runaway stellar merging. After the clusters dissolve, these IMBHs continue their inward drift, carrying a few of the most massive stars with them. We predict that a region within ~ 10 pc of the supermassive black hole (SMBH) is populated by ~ 50 IMBHs of $\sim 1000 M_\odot$. Several of these are still expected to be accompanied by some of the most massive stars from the star cluster. We also find that within a few milliparsecs of the SMBH there is a steady population of several IMBHs. This population drives the merger rate between IMBHs and the SMBH at a rate of about one per 10 Myr, sufficient to build the accumulated majority of mass of the SMBH. Mergers of IMBHs with SMBHs throughout the universe are detectable by *LISA* at a rate of about two per week.

Subject headings: black hole physics — Galaxy: center*Online material:* color figure

1. INTRODUCTION

In recent years the Galactic center has been explored extensively over most of the electromagnetic spectrum, revealing complex structures and a multitude of intriguing physical phenomena. At the center lies a $\sim 3.7 \times 10^6 M_\odot$ black hole (Eckart & Genzel 1997; Ghez et al. 1998, 2000). The presence of a water-rich dust ring at about 1 pc from Sgr A* (Sandqvist et al. 2003) further underscores the complexity of this region, as does the presence within the central parsec of a few million year old population of very massive Ofpe/WN9 (Tamblyn & Rieke 1993) and luminous blue variable stars (Najarro et al. 1997). These young stars may indicate recent star formation in the central region (Morris 1993; Nayakshin & Sunyaev 2005), or they may have migrated inward from larger distances to their current locations (Gerhard 2001). In addition, the *Chandra X-Ray Observatory* has detected an unusually large number ($\gtrsim 2000$) of hard X-ray (2–10 keV) point sources within 23 pc of the Galactic center (Muno et al. 2003). Seven of these sources are transients and are conjectured to contain stellar-mass black holes (Muno et al. 2004); some may even harbor intermediate mass black holes (IMBHs; Menou et al. 2001).

The Galactic center is a dynamic environment, where young stars and star clusters form in molecular clouds (Lada & Lada 2003) or thick dusty rings (Nayakshin & Cuadra 2004; Nayakshin

& Sunyaev 2005) and interact with their environment. Several star clusters are known to exist in this region (Figer et al. 1999a), and the star formation rate in the inner bulge is estimated to be comparable to that in the solar neighborhood (Portegies Zwart et al. 2001a), enough to grow the entire bulge over the age of the Galaxy.

Of particular interest here are the several star clusters discovered within ~ 100 pc of the Galactic center, 11 of which have reliable mass estimates (Borissova et al. 2005). Most interesting of these are the two dense and young ($\lesssim 10$ Myr) star clusters Arches (Figer et al. 2002) and the Quintuplet (Figer et al. 1999b), and the recently discovered groups IRS 13E (Maillard et al. 2004) and IRS 16SW (Lu et al. 2005).

In this paper we study the relation between the star clusters in the inner ~ 100 pc of the Galactic center and, to some extent, the partial formation of the central supermassive black hole. In particular, we simulate the evolution of the star clusters born over a range of distances from the Galactic center. While we follow their internal dynamical evolution, we allow the star clusters to spiral inward toward the Galactic center until they dissolve in the background. During this process a runaway collision may have occurred in the cluster, and we follow the continuing spiral-in of the resulting IMBH.

Our prescription for building an IMBH has been well established in numerous papers concerning stellar collision runaways in dense star clusters (Quinlan & Shapiro 1990; Portegies Zwart et al. 1999; Figer & Kim 2002; Gürkan et al. 2004; Gürkan & Rasio 2005; Freitag et al. 2005a). We just build on these earlier results for our description of the collision runaway and the way in which it leads to the formation of a black hole of intermediate mass.

Eventually, the IMBHs merge with the supermassive black hole (SMBH), building the SMBH in the process. This model was initially proposed by Ebisuzaki et al. (2001), and here we validate the model by detailed simulations of the dynamical evolution of individual star clusters and the final spiral-in of the IMBH toward

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the SMBH. Using the results of the direct N -body simulations, we calibrate a semianalytic model to simulate a population of star clusters that are born within ~ 100 pc over the age of the Galaxy.

2. COLLISION RUNAWAYS AND CLUSTER INSPIRAL

A substantial fraction of stars are born in clusters, and these have power-law stellar mass functions fairly well described by a “Salpeter” exponent of -2.35 , and with stellar masses ranging from the hydrogen burning limit ($\sim 0.08 M_\odot$) or a bit above (Stolte et al. 2005) to an upper limit of $\sim 100 M_\odot$ or possibly as high as $150 M_\odot$ (Figer 2005). The massive stars start to sink to the cluster center immediately after birth, driving the cluster into a state of core collapse on a timescale $t_{\text{cc}} \simeq 0.2 t_{\text{th}}$ (Portegies Zwart & McMillan 2002; Gürkan et al. 2004), where (Spitzer & Hart 1971)

$$t_{\text{th}} \simeq 2 \text{ Myr} \left(\frac{r}{1 \text{ pc}} \right)^{3/2} \left(\frac{m}{1 M_\odot} \right)^{-1/2} \frac{n}{\log \lambda}. \quad (1)$$

Here m is the cluster mass, r is its half-mass radius, n is the number of stars, and $\log \lambda \simeq \log(0.1n) \sim 10$. In sufficiently compact clusters the formation of a dense central subsystem of massive stars may lead to a “collision runaway,” where multiple stellar mergers result in the formation of an unusually massive object (Portegies Zwart et al. 1999; Portegies Zwart & McMillan 2002; Gürkan et al. 2004; Freitag et al. 2005a). If the mass of this runaway grows beyond $\sim 300 M_\odot$, it collapses to an IMBH without losing significant mass in a supernova explosion (Heger et al. 2003). Recently, this model has been applied successfully to explain the ultraluminous X-ray source associated with the star cluster MGG-11 in the starburst galaxy M82 (Portegies Zwart et al. 2004a). This model for creating an IMBH in a dense star cluster was adopted by Gürkan & Rasio 2005, who continued by studying the evolution of massive $\geq 10^6 M_\odot$ star clusters within about 60 pc from the Galactic center. Their conclusions are consistent with the earlier N -body models (Kim et al. 2000; Portegies Zwart et al. 2003; McMillan & Portegies Zwart 2003; Kim et al. 2004) and analytic calculations (Gerhard 2001) in that massive clusters can reach the Galactic center, but in doing so they populate the inner few parsecs with a disproportionately large number of massive stars.

The main requirement for a successful collision runaway is that the star cluster must experience core collapse before (1) the most massive stars explode as supernovae (~ 3 Myr) and (2) the cluster dissolves in the Galactic tidal field. The collisional growth rate slows dramatically once the runaway collapses to an IMBH. We estimate the maximum runaway mass achievable by this process as follows. For compact clusters ($t_{\text{th}} \lesssim 100$ Myr), essentially all the massive stars reach the cluster core during the course of the runaway, and the runaway mass scales with the cluster mass: $m_r \simeq 8 \times 10^{-4} m \log \lambda$ (Portegies Zwart & McMillan 2002). For systems with longer relaxation times, only a fraction of the massive stars reach the core in time, and the runaway mass scales as $m_r t_{\text{th}}^{-1/2}$ (McMillan & Portegies Zwart 2004; see their eq. [11]). The relaxation-based argument may result in higher mass runaways in star clusters with a very small relaxation time compared to the regime studied in Monte Carlo N -body simulations (McMillan & Portegies Zwart 2004). A convenient fitting formula combining these scalings, calibrated by N -body simulations for Salpeter-like mass functions, is

$$m_r \sim 0.01 m \left(1 + \frac{t_{\text{th}}}{100 \text{ Myr}} \right)^{-1/2} \quad (2)$$

(Portegies Zwart & McMillan 2002; McMillan & Portegies Zwart 2004). Early dissolution of the cluster reduces the runaway mass by prematurely terminating the collision process.

As core collapse proceeds, the orbit of the cluster decays by dynamical friction with the stars comprising the nuclear bulge. The decay of a circular cluster orbit of radius R is described by

$$\frac{dR}{dt} = -0.43 \frac{Gm \log \Lambda}{R^{(\alpha+1)/2} v_c}, \quad (3)$$

(see eqs. [7]–[25] in Binney & Tremaine [1987] or McMillan & Portegies Zwart [2003] for the more general case), where $v_c^2 = GM(R)/R$, $\alpha = 1.2$, $M(R)$ is the mass within a distance R from the Galactic center, and we take $\log \Lambda \sim 8$ (Spinnato et al. 2003). Numerical solution of this equation is required due to the complicating effects of stellar mass loss, which drives an adiabatic expansion of the cluster, and by tidal stripping, whereby the cluster mass tends to decrease with time according to $m(t) = m_0(1 - \tau/t_{\text{dis}})$ (Portegies Zwart & McMillan 2002). Here m_0 is the initial mass of the cluster, τ is the cluster age in terms of the instantaneous relaxation time (t_r) within the Jacobi radius, and t_{dis} is the timescale for cluster disruption: $t_{\text{dis}} \simeq 0.29 t_r$.⁸

Even after the bulk of the cluster has dissolved, a dense stellar cusp remains surrounding the newborn IMBH and accompanies it on its descent toward the Galactic center. The total mass of stars in the cusp is typically comparable to that of the IMBH itself (Baumgardt et al. 2004), and it is composed predominantly of massive stars, survivors of the population that initiated the core collapse during which the IMBH formed. Eventually, even that cusp slowly decays by two-body relaxation (Hansen & Milosavljević 2003), depositing a disproportionately large number of massive stars and the orphaned IMBH close to the Galactic center (Gürkan & Rasio 2005). Ultimately, the IMBH merges with the SMBH.

3. SIMULATING STAR CLUSTERS WITHIN ~ 100 PC FROM THE GALACTIC CENTER

We have performed extensive direct N -body calculations to test the validity of the general scenario presented above and to calibrate the semianalytic model. Our analysis combines several complementary numerical, analytical, and theoretical techniques in a qualitative model for the formation and evolution of the nuclear bulge of the Milky Way. The semianalytical model outlined in § 2, which is based on equation (3) of McMillan & Portegies Zwart (2003), is based on simple characterizations of physical processes, which we calibrate using large-scale N -body simulations. The initial conditions for these simulations are selected to test key areas in the parameter space for producing IMBHs in the inner ~ 100 pc of the Galactic center.

The N -body calculations employ direct integration of Newton’s equations of motion, while accounting for complications such as dynamical friction and tidal effects due to the Galactic field, stellar and binary evolution, physical stellar sizes, the possibility of collisions, and the presence of a supermassive black hole in the Galactic center. Two independent but conceptually similar programs are used: (1) the *kira* integrator, part of the Starlab software environment (Portegies Zwart et al. 2001b),⁹ and

⁸ Theoretical considerations suggest that the timescale for cluster dissolution has the form $t_{\text{dis}} = k t_{\text{hc}}^{1/4} t_{\text{th}}^{3/4}$, where t_{hc} is the cluster crossing time (Baumgardt & Makino 2003). The constant k may be obtained from direct N -body simulations of star clusters near the Galactic center (Portegies Zwart et al. 2001a), resulting in $k \simeq 7.5$, with t_{hc} and t_{th} expressed in Myr.

⁹ See <http://www.manybody.org/~manybody/starlab.html>.

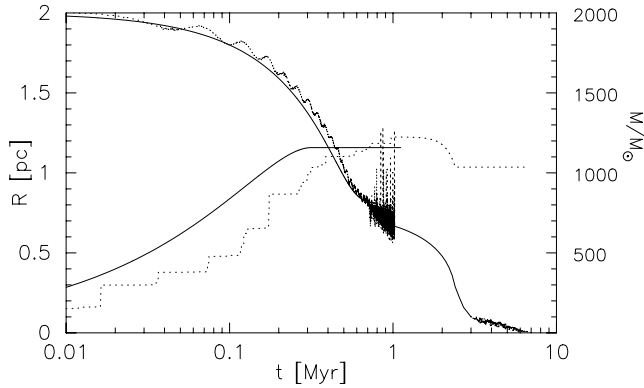


FIG. 1.—Orbital evolution of a star cluster. A $45,000 M_{\odot}$ cluster of 65,536 stars with a Salpeter initial mass function, a lower mass limit of $0.2 M_{\odot}$, and a $W_0 = 9$ King model initial density profile spirals in to the Galactic center from a distance of 2 pc (lines from top left to bottom right), while producing an IMBH via collision runaway (bottom left to top right; scale on the right axis). Solid lines (based on eq. [3]) show the results of the semianalytic model (with $\log \Lambda = 8$), and the dotted lines represent high-precision N -body calculations. The solid and dotted lines match quite well, indicating that the analytic model produces satisfactory results.

(2) NBODY4 (Aarseth 2003).¹⁰ Both codes achieve their greatest speed, as in the simulations reported here, when run in conjunction with the special-purpose GRAPE-6¹¹ hardware acceleration (Makino et al. 2003).

Both kira and NBODY4 incorporate parametrized treatments of stellar evolution and allow for the possibility of direct physical collisions between stars, thus including the two key physical elements in the runaway scenario described here (see also Portegies Zwart et al. 2004a). A collision occurs if the distance between two stars becomes smaller than the sum of the stellar radii, except that, for collisions involving black holes, we use the tidal radius instead. During a collision, mass and momentum are conserved. These are reasonable assumptions since the relative velocity of any two colliding stars is typically much smaller than the escape speed from either stellar surface (Lombardi et al. 2003; Freitag & Benz 2005).

We performed N -body simulations of star clusters containing up to 131,072 stars and starting at $R = 1, 2, 4, 10$ and 100 pc from the Galactic center, with various initial concentrations ($W_0 = 6$ and 9) and with lower limits to the initial mass function of 0.1 and $1 M_{\odot}$. These simulations were carried out as part of the calibration of the semianalytic model, which we present in § 5.

One such comparison is presented in Figure 1, which shows the orbital evolution and runaway growth in a star cluster born with 65,536 stars in a circular orbit at a distance of 2 pc from the Galactic center. The solid lines in the figure result from the semianalytic model (based on eq. [3] and McMillan & Portegies Zwart 2003), while the high precision N -body calculations are represented by dotted lines. They match quite well, indicating that the simple analytic model produces satisfactory results in reproducing the general features and physical scales of the evolution.

As the cluster in Figure 1 sinks toward the Galactic center, it produces one massive star through the collision runaway process. In Figure 2 we show a snapshot of this simulation projected in three different planes at an age of 0.35 Myr. By this time $\sim 30\%$ of the cluster has already dispersed, and its stars have spread out

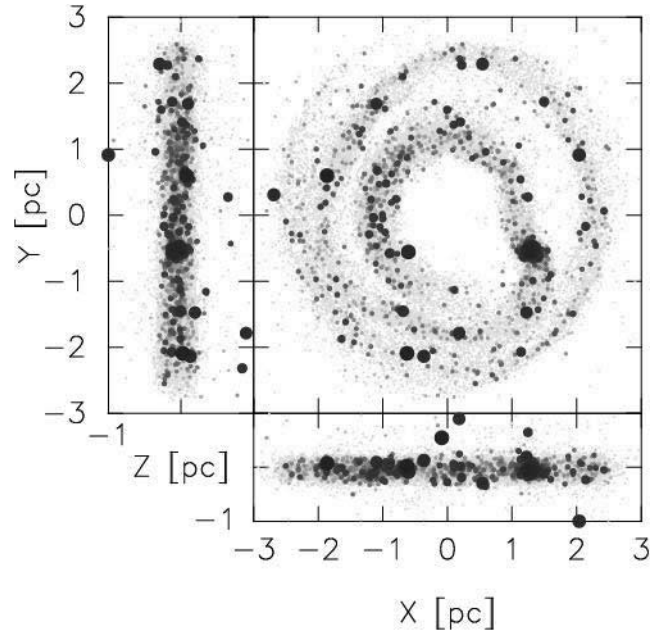


FIG. 2.—Snapshot of a dissolving cluster, showing the projection on various planes of the N -body simulation shown in Fig. 1, at a cluster age of 0.35 Myr. The cluster initially orbited in the X - Y plane in a circular counterclockwise orbit at a distance of 2 pc from the Galactic center. By the time shown the cluster has lost about 30% of its initial mass. However, the majority of massive stars are still bound to the IMBH progenitor as it orbits the Galactic center at a distance of roughly 1.2 pc. The individual stars shown range in mass from 0.2 to $100 M_{\odot}$, with symbol sizes proportional to the surface area of each star. Color runs from red (cool) to blue (hot). [See the electronic edition of the *Journal* for a color version of this figure.]

into the shape of a disk spanning the inward-spiraling orbit. By the time of Figure 2, a $\sim 1100 M_{\odot}$ collision runaway star has formed in the cluster center; this object subsequently continues to grow by repeated stellar collisions. The growth of the collision runaway is indicated by the dotted line in Figure 1 running from bottom left to top right (scale on the right vertical axis).

By an age of about 0.7 Myr the cluster is almost completely disrupted and the runaway process terminates. After the cluster dissolves, the IMBH continues to sink toward the Galactic center, still accompanied by 10–100 stars that initially were among the most massive in the cluster.

Near the end of its lifetime, the runaway star loses about $200 M_{\odot}$ in a stellar wind and subsequently collapses to a $\sim 1000 M_{\odot}$ IMBH at about 2.4 Myr. The IMBH and its remaining stellar companions continue to sink toward the Galactic center. The continuing “noise” in the dotted curve in Figure 1 reflects the substantial eccentricity of the IMBH orbit. At an age of 2.5–3 Myr, the remnant star cluster consisting of an IMBH orbited by a few of the most massive stars, quite similar to the observed star cluster IRS 13, arrives in the inner 0.1 pc of the Galaxy (see § 7).

4. MERGER WITH THE CENTRAL BLACK HOLE

When the IMBH arrives within about 0.1 pc of the Galactic center, the standard formula for dynamical friction (Binney & Tremaine 1987) is becoming unreliable, as the background velocity dispersion increases and the effects of individual encounters become more significant. It is important, however, to ascertain whether the IMBH spirals all the way into the SMBH, or if it stalls in the last tenth of a parsec, as higher mass black holes tend to do (Merritt & Wang 2005).

¹⁰ See <http://www.sverre.org>.

¹¹ See <http://www.astrogrape.org>.

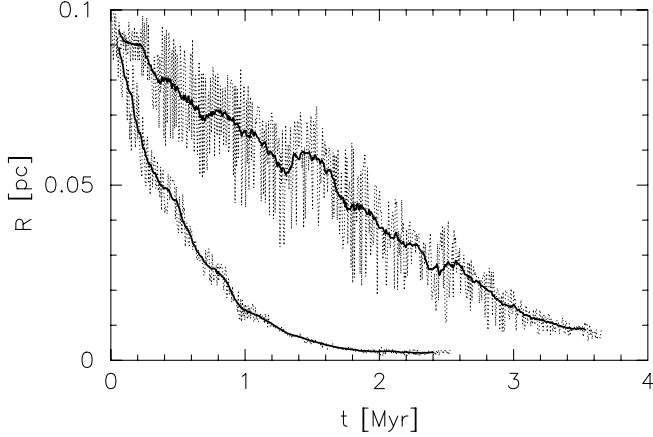


FIG. 3.—Final orbital evolution of two IMBHs, of masses $1000 M_{\odot}$ (right curve) and $3000 M_{\odot}$ (left curve), each starting from a circular orbit of radius 0.1 pc and ending at the center of the Galaxy, where the IMBHs ultimately merge with the SMBH there. The dotted lines show the actual orbits, while the solid lines have been smoothed over several orbits to filter out the short-timescale fluctuations due to orbital eccentricity. The final merger occurs on a timescale similar to the time interval between successive IMBH arrivals in the central parsec, driving the growth by accretion of the central black hole.

To determine the time required for the IMBH to reach the central SMBH, we have performed additional N -body calculations, beginning with a 1000 and a $3000 M_{\odot}$ IMBH in circular orbits at a distance of 0.1 pc from the Galactic center. Both IMBHs are assumed to have shed their parent cluster by the start of the simulation. The inner parsec of the Galaxy is modeled by 131,071 identical stars with a total stellar mass of $4 \times 10^6 M_{\odot}$, distributed according to a $R^{-1.75}$ density profile; a black hole of $3 \times 10^6 M_{\odot}$ resides at the center. The region within a milliparsec of the central SMBH is depleted of stars in our initial conditions. This is supported by the fact that the total Galactic mass inside that radius, excluding the central SMBH is probably less than $10^3 M_{\odot}$ (Ghez et al. 1998; Genzel et al. 2003). We stop the calculations as soon as the IMBH reaches this distance.

Figure 3 (see also Fig. 1, dotted line) shows the orbital evolution of the 1000 and $3000 M_{\odot}$ IMBHs in our simulations. Although the black hole orbits are initially circular, eccentricities on the order of $\lesssim 0.6$ are induced quite quickly by close encounters with field stars. The rate of spiral-in near the SMBH is smaller than that farther out, because the increasing velocity dispersion tends to reduce the effect of dynamical friction and because the IMBH reaches the inner depleted area.

The central milliparsec was initially empty in our simulations, and there was insufficient time to replenish it during our calculations. It is unlikely that sufficient stellar mass exists within this region for dynamical friction to drive the IMBH much closer to the SMBH. (Interestingly, this distance is comparable to the orbital semimajor axis of the star S0-2, which is observed in a 15 yr orbit around the Galactic center (Ghez et al. 2003). The timescale for a 1 mpc orbit to decay by gravitational radiation exceeds the age of the Galaxy for circular motion, so unless the IMBH orbit is already significantly eccentric or is later perturbed to higher eccentricity ($\gtrsim 0.9$ to reduce the merger time to $\lesssim 10^9$ yr) by encounters with field stars or another IMBH, the orbital decay effectively stops near the central SMBH.

While the IMBH stalls, another star cluster may form, sink toward the Galactic center, and give rise to a new IMBH, which subsequently arrives in the inner milliparsec (see § 5). This process will be repeated for each new IMBH formed, until interactions become frequent enough to drive a flux of IMBHs into the

loss cone where gravitational radiation can complete the merger process.

We can estimate the number of IMBHs in a steady state in the inner few milliparsecs of the SMBH. The timescale for a close (90° deflection) encounter in a system of n_{IMBH} IMBHs is

$$t_{\text{close}} \sim \left(\frac{M_{\text{SMBH}}}{m_{\text{IMBH}}} \right)^2 \frac{t_{\text{orb}}}{n_{\text{IMBH}}}, \quad (4)$$

where M_{SMBH} and m_{IMBH} are the masses of the SMBH and the IMBH, respectively, and $t_{\text{orb}} \sim 1\text{--}10$ yr is the typical orbital period at a distance of 1 mpc from the SMBH. For $M_{\text{SMBH}} \sim 10^6 M_{\odot}$ and $m_{\text{IMBH}} \sim 10^3 M_{\odot}$, we find $t_{\text{close}} \sim (1\text{--}10) \times 10^6 / n_{\text{IMBH}}$ yr, comparable to the in-fall timescale unless n_{IMBH} is large.

Close encounters are unlikely to eject IMBHs from the vicinity of the Galactic center, but they do drive the merger rate by replenishing the loss cone around the SMBH (Merritt & Poon 2004; Gültekin et al. 2004). As IMBHs accumulate, the cusp around the SMBH eventually reaches a steady state in which the merger rate equals the rate of in-fall, with a roughly constant population of a few IMBHs within about a milliparsec of the SMBH. A comparable analysis was performed by Alexander & Livio (2004) for stellar-mass black holes around the SMBH, and if we scale their results to IMBHs we arrive at a similar steady state population.

5. THE EVOLUTION OF A POPULATION OF STAR CLUSTERS

We now turn to the overall evolution of the population of clusters that gave rise to the nuclear bulge. We have performed a Monte Carlo study of the cluster population, adopting a star formation rate that declines as $1/t$ over the past 10 Gyr (Heavens et al. 2004). Cluster formation times are selected randomly following this star formation history, and masses are assigned as described below, until the total mass equals the current mass of the nuclear bulge within 100 pc of the Galactic center—about $10^9 M_{\odot}$. The total number of clusters thus formed is $\sim 10^5$ over the 10 Gyr period.

For each cluster, we select a mass (m) randomly from a cluster initial mass function, which is assumed to follow the mass distribution observed in starburst galaxies—a power law of the form $N(m) \propto m^{-2}$ between $\sim 10^3$ and $\sim 10^7 M_{\odot}$ (Zhang & Fall 1999). The distance to the Galactic center (R) is again selected randomly, assuming that the radial distribution of clusters follows the current stellar density profile in the bulge between 1 and 100 pc (Eckart & Genzel 1997; Ghez et al. 1998). The current distribution of stars must reflect the formation distribution to a large extent, because most stars' orbits do not evolve significantly, only the orbits of the more massive stellar clusters. The initial density profiles of the clusters are assumed to be $W_0 = 6\text{--}9$ King models. This choice of high-concentrated King models is supported by the recent theoretical understanding by Merritt et al. (2004) of the relation between age and core radius for young star clusters in the large Magellanic cloud observed by Mackey & Gilmore (2003).

We establish a cluster mass-radius relation by further assuming that clusters are born precisely filling their Jacobi surfaces in the Galactic tidal field. This provides a lower limit to the fraction of clusters that produce an IMBH and sink to the Galactic center.

The evolution of each cluster, including specifically the moment at which it undergoes core collapse, the mass of the collision runaway (if any) produced, and the distance from the

Galactic center at which the cluster dissolves is then calculated deterministically using our semianalytic model. After cluster disruption, the IMBH continues to sink by dynamical friction, eventually reaching the Galactic center.

5.1. Results of the Cluster Population Model

Figure 4 summarizes the dependence of the fates of the star clusters in our simulation on m and R . Open and filled circles represent initial conditions that result in an IMBH reaching the central parsec by the present day. The various lines define the region of parameter space expected to contribute to the population of IMBHs within the central parsec, as described in the caption. Here we emphasize that our results depend linearly on the fraction of stars in the bulge that form in star clusters. The number of star clusters and IMBHs is proportional to this factor, which is not necessarily constant with time. Also bear in mind that, although theoretical uncertainties are about a factor of 2, the systematic uncertainties can be much larger and depend critically on various assumptions in the models, like the amount of mass loss in the stellar wind of the collision product and the fate of the stellar remnant in the supernova explosion. The results of our calculations may be summarized as follows:

1. 5%–10% of star clusters born within 100 pc of the Galactic center produce an IMBH.
2. The mean mass of IMBHs now found in the inner 10 pc is $\sim 1000 M_\odot$, whereas IMBHs between 90 and 100 pc average $\sim 500 M_\odot$.
3. Over the age of the Galaxy ($\sim 10^{10}$ yr) a total of 1000–3000 IMBHs have reached the Galactic center, carrying a total mass of $\sim 1 \times 10^6 M_\odot$. Here the range in masses stems from variations in the adopted stellar mass function.
4. At any instant, approximately ~ 50 IMBHs reside in the inner 10 pc, about 10 times that number lie within the nuclear star cluster (inner 30 pc), and several lie within the innermost few tenths of a parsec.
5. One in every ~ 30 IMBHs is still accompanied by a remnant of its young (turn-off mass $\gtrsim 10 M_\odot$) star cluster when it reaches the inner parsec, resulting in a few IMBHs at any time in the inner few parsecs with young stars still bound to them, much like IRS 13E or IRS 16SW.

On the basis of our N -body simulations of the central 0.1 pc in § 4, we expect that the majority of IMBHs that arrive in the Galactic center eventually merge with the SMBH on a timescale of a few Myr, driven by the emission of gravitational radiation and interactions with local field stars and other IMBHs. In our simulations the in-fall rate has increased over the lifetime of the Galaxy (following our assumed star formation rate), from one arrival per ~ 20 Myr to the current value of one every ~ 5 Myr, with a time average IMBH in-fall rate of roughly one per ~ 7 Myr. (A lower minimum mass in the initial mass function produces higher in-fall rates.)

Some of the field stars near the SMBH may be ejected from the Galactic center with velocities of up to ~ 2000 km s $^{-1}$ following encounters with the hard binary system formed by the IMBH and the central SMBH (Hills 1988; Yu & Tremaine 2003; Gualandris et al. 2005). Support for this possibility comes from the recent discovery of SSDS J090745.0+024507, a B9 star with a measured velocity of 709 km s $^{-1}$ directly away from the Galactic center (Brown et al. 2005).

IMBHs are potentially important sources of gravitational wave radiation. A merger between a $1000 M_\odot$ IMBH and a $\sim 3 \times 10^6 M_\odot$ SMBH would be detectable by the *Laser Interferometer Space Antenna* (LISA) gravitational wave detector to a distance of sev-

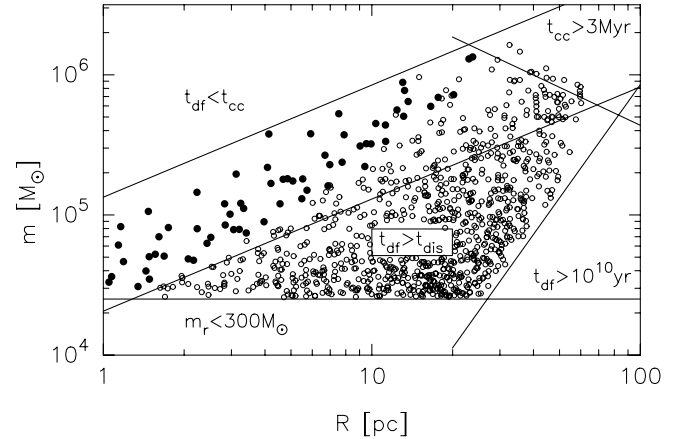


FIG. 4.—Parameter space for the formation of IMBHs. Within the semi-analytic model, the initial mass of a star cluster (m) and its initial distance from the Galactic center (R) determine its fate and control whether or not an IMBH forms. For the initial mass function for the cluster stars, we choose a Salpeter distribution between 0.2 and $100 M_\odot$ and King $W_0 = 9$. The lines separate the various regions of the parameter space investigated. Star clusters born in the top left part of the diagram ($t_{dr} < t_{cc}$) spiral inward and dissolve in the Galactic field before core collapse can occur. At the top right ($t_{cc} > 3$ Myr), the most massive stars in the cluster leave the main sequence before core collapse has occurred, thus preventing a collision runaway. Clusters born with masses less than a few $10^4 M_\odot$ cannot form a sufficiently massive collision product ($m_r < 300 M_\odot$), and clusters to the right and below the middle solid curve ($t_{dr} > t_{dis}$) dissolve before they reach the central parsec. To the right of and below the rightmost diagonal line ($t_{dr} > 10^{10}$ yr), there is insufficient time for IMBHs to form and sink to the center of the Galaxy. Open and filled circles represent initial conditions that result in an IMBH reaching the central parsec by the present day. Filled circles indicate that part of the parent star cluster is still present on arrival. Open circles represent cases in which the IMBH continued to sink to the Galactic center even after its parent star cluster dissolved, typically at a rather large distance from the Galactic center. The two sets of symbols are roughly separated by the line for which the disruption time equals the dynamical friction time-scale: $t_{dr} = t_{dis}$.

eral billion parsecs. Assuming that the processes just described operate in most spiral galaxies, which have a density of roughly 0.002 Mpc^{-3} (Kauffmann et al. 2004), we estimate a detectable IMBH merger rate of around two per week, with a signal-to-noise ratio $\sim 10^3$.

5.2. The Current Cluster Population

Our semianalytic model for the evolution of star clusters in the inner ~ 100 pc of the Galaxy yields a steady state distribution of cluster masses that we can compare with observed star clusters in the vicinity of the Galactic center. Figure 5 compares the observed mass distribution of young star clusters in the bulge with our steady state solution. The data include the Arches cluster (Figer et al. 2002), the Quintuplet (Figer et al. 1999b), IRS 13E (Maillard et al. 2004), IRS 16SW (Lu et al. 2005), and seven recently discovered star clusters with reliable mass estimates (Borissova et al. 2005). For comparison, we show a realization of the present-day population of star cluster masses generated by our semianalytic model.

Using the adopted declining star formation rate from § 5 (see Heavens et al. 2004), we find about ~ 50 star clusters within the central 100 pc at any given time, consistent with the earlier prediction of Portegies Zwart et al. (2001a). Assuming a flat (i.e., uniform) star formation rate, we predict ~ 400 clusters in the same region, about an order of magnitude more than that currently observed. In our semianalytic model, about 15% of all present-day star clusters host an IMBH or are in the process of producing one. Between 1% and 8% of star clusters with a present-day mass

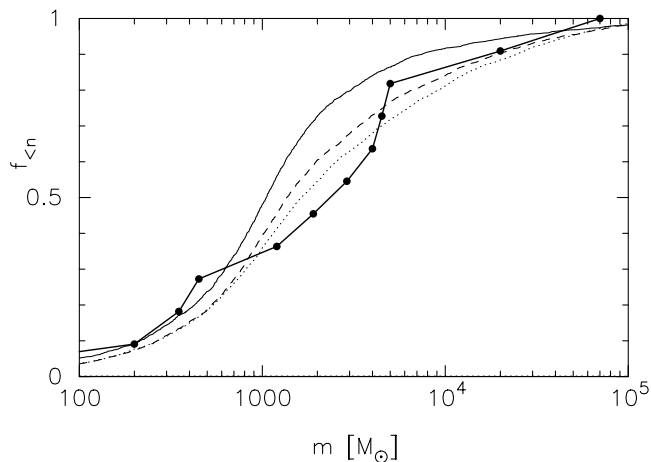


FIG. 5.—Cumulative distribution of star clusters in the vicinity of the Galactic center. The thick solid curve gives the masses of 11 observed Galactic center clusters (*filled circles*) with reliable mass estimates (Borissova et al. 2005; Figer et al. 1999a). The other curves give the distribution of cluster masses from our semianalytic model. The theoretical curves are quite insensitive to the star formation history but change with the lower mass limit adopted for the cluster initial mass function. The lower limit is $1 M_{\odot}$ for the thin solid curve, $0.2 M_{\odot}$ for the dashed curve, and $0.1 M_{\odot}$ for the dotted curve. The number of observable clusters is best matched with the decaying star formation rate adopted in § 5.

less than $10^4 M_{\odot}$ contain an IMBH, whereas more than 80% of clusters with masses between 30,000 and $2 \times 10^5 M_{\odot}$ host an IMBH. For more massive clusters the probability of forming an IMBH drops sharply.

Finally, we note that we are rather unlikely to find an orphaned very massive ($\gtrsim 200 M_{\odot}$) star. During the last 1 Gyr, only about 10–40 of such objects have formed in the inner 100 pc of the Galaxy. Lower mass merger products, however, are quite common. The Pistol star (Figer et al. 1999b) may be one observational example.

6. DISCUSSION

6.1. Evolution of the Merger Product

One of the main uncertainties in our calculations is whether mass gain by stellar collisions exceeds mass loss by stellar winds. Although the accretion rate in our models is very high, mass-loss rates in massive stars are uncertain, and it is conceivable that sufficiently high mass-loss rates might prevent the merger product from achieving a mass of more than a few hundred M_{\odot} .

Mass loss in massive ($\gtrsim 100 M_{\odot}$) stars may be radiatively driven by optically thin lines. In this case it is possible to derive upper limits to the mass loss. Such calculations, including the von Zeipel (1924) effect for stars close to the Eddington-Gamma limit, indicate that stellar wind mass-loss rates may approach $10^{-3} M_{\odot} \text{ yr}^{-1}$ (Vink et al. 2000). If the star is rotating near the critical rate, the mass-loss rate may be even larger (Aerts et al. 2004). Outflow velocities, however, may be so small that part of the material falls back on the equatorial zone, where the mass loss is least (Aerts et al. 2004). The calculations of Aerts et al. (2004) match the observed mass-loss rates for η Car, which has a peak of $(1.6 \pm 0.3) \times 10^{-3} M_{\odot} \text{ yr}^{-1}$ (assuming spherical symmetry) during normal outbursts, falling to $10^{-5} M_{\odot} \text{ yr}^{-1}$ during the intervening 5.5 yr (van Boekel et al. 2003). For young ($\lesssim 4$ Myr) O stars in the small Magellanic cloud, low ($\lesssim 10^{-8} M_{\odot} \text{ yr}^{-1}$) mass-loss rates were observed (Martins et al. 2004), indicating that massive stars may have much lower mass-loss rates until they approach the end of their main-sequence lifetimes (see Meynet & Maeder 2003).

Thus, it remains unclear whether the periods of high mass loss persist long enough to seriously undermine the runaway scenario adopted here. We note that the collision runaways in our simulations are initiated by the arrival of a massive star in the cluster core (Portegies Zwart et al. 1999). If such a star grows to exceed $\sim 300 M_{\odot}$, most collisions occur within the first 1.5 Myr of the cluster evolution. The collision rate during the period of rapid growth typically exceeds one per $\sim 10^4$ yr, sustained over about 1 Myr, resulting in an average mass accretion rate exceeding $10^{-3} M_{\odot} \text{ yr}^{-1}$, comparable to, and possibly exceeding, the maximum mass-loss rates derived for massive stars. Furthermore, in our N -body simulations (and in the semianalytic model), the stellar mass-loss rate increases with time, with little mass loss at the zero-age main sequence and substantially more near the end of the main-sequence stellar lifetime ($\dot{m}_{\text{wind}} \propto L^{2.2}$; Vink et al. 2000; Langer et al. 1994; Kudritzki 2002). In other words, mass-loss rates are relatively low while most of the accretion is occurring. This prescription for the mass-loss rate matches that of evolutionary calculations for massive Wolf-Rayet stars (Meynet & Maeder 2005).

We also emphasize that a large mass-loss rate in the merger product *cannot* prevent the basic mass segregation and collision process, even though it might significantly reduce the final growth rate (Portegies Zwart et al. 1999). These findings are consistent with recent N -body simulations of small clusters in which the assumed mass-loss rate from massive ($> 120 M_{\odot}$) stars exceeded $10^{-3} M_{\odot} \text{ yr}^{-1}$ (Belkus et al. 2004).

The stellar evolution of a runaway merger product has never been calculated in detail and is poorly understood. However, it is worth mentioning that its thermal timescale significantly exceeds the mean time between collisions. Even if the star grows to $\gtrsim 10^3 M_{\odot}$, the thermal timescale will be $(1\text{--}4) \times 10^4$ yr, still comparable to the collision rate. The accreting object will therefore be unable to reestablish thermal equilibrium before the next collision occurs.

We note in passing that the supermassive star produced in the runaway collision may be hard to identify by photometry if the cluster containing it cannot be resolved: The runaway is mainly driven by collisions between massive stars, which themselves have luminosities close to the Eddington-Gamma limit. Since the Eddington luminosity scales linearly with mass, a collection of luminous blue variables at the Eddington luminosity are comparable in brightness to an equally massive single star. Spectroscopically, however, the collision runaway may be very different.

Mass loss in the form of a dense stellar wind before the supernova can dramatically reduce the mass of the final black hole or could even prevent black hole formation altogether (Heger et al. 2003). The runaway merger in Figure 1 develops a strong stellar wind near the end of its lifetime before collapsing to a $\sim 1000 M_{\odot}$ IMBH at ~ 2.4 Myr. It is difficult to quantify the effect of stellar winds on the final IMBH mass because the mass-loss rate of such a massive star remains uncertain (Vink et al. 2001). However, it is important to underscore here the qualitative results that stellar winds are unable to prevent the occurrence of repeated collisions and significantly limit the outcome only if the mass-loss rate is very high—more than $\sim 10^{-3} M_{\odot} \text{ yr}^{-1}$ —and sustained over the lifetime of the star.

7. THE STAR CLUSTERS IRS13E AND IRS16SW

The best IMBH candidate in the Milky Way was recently identified in the young association IRS 13E in the Galactic center region. IRS 13E is a small cluster of stars containing three spectral type O5 I to O5 III and four Wolf-Rayet stars, totaling at most $\sim 300 M_{\odot}$ (Maillard et al. 2004; Schödel et al. 2005). (The

recently discovered cluster IRS 16SW [Lu et al. 2005] also lies near the Galactic center and reveals similarly interesting stellar properties.) Both clusters are part of the population of helium-rich bright stars in the inner parsec of the Galactic center (Paumard et al. 2001). With a “normal” stellar mass function, as found elsewhere in the Galaxy, stars as massive as those in IRS 13E are extremely rare, occurring only once in every ~ 2000 stars. However, in the Galactic center, a “top-heavy” mass function may be common (Figer 2004; Stolte et al. 2005).

The mean proper motion of five stars in IRS 13E is $\langle v \rangle_{2D} = 245 \text{ km s}^{-1}$ (Schödel et al. 2005); an independent measurement of four of these stars yields 270 km s^{-1} (Maillard et al. 2004). If IRS 13E were part of the rotating central stellar disk (Genzel et al. 2003), this would place the cluster $\sim 0.12 \text{ pc}$ behind the plane on the sky containing the SMBH, increasing its galactocentric distance to about 0.18 pc , consistent with a circular orbit around the SMBH at the observed velocity. The five IRS 16SW stars have $\langle v \rangle_{2D} \simeq 205 \text{ km s}^{-1}$ (Lu et al. 2005), corresponding to the circular orbit speed at a somewhat larger distance ($\sim 0.4 \text{ pc}$).

The greatest distance between any two of the five stars in IRS 13E with known velocities is $\sim 0.5''$ (0.02 pc at 8.5 kpc), (Maillard et al. 2004; Schödel et al. 2005) providing a lower limit on the Jacobi radius: $r_J \gtrsim 0.01 \text{ pc}$. It then follows from the Hills equation ($r_J^3 \simeq R^3 m/M$) that the minimum mass required to keep the stars in IRS 13E bound is about $1300 M_\odot$ (see also Maillard et al. 2004).

A more realistic estimate is obtained by using the measured velocities of the observed stars, using the expression $m = \langle v^2 \rangle R/G$. The velocity dispersion of all stars, E1, E2, E3, E4, and E6, is about $\langle v \rangle \simeq 68\text{--}84 \text{ km s}^{-1}$, which results in an estimated mass of $\sim 11,000\text{--}16,000 M_\odot$. Such a high mass would be hard to explain with the collision runaway scenario.

However, the stars E1 and E6 may not be members. The extinction of the latter star is smaller than that of the other stars, indicating that it may be closer to the Sun than the rest of the cluster and therefore not a member (Schödel et al. 2005). One could also argue that star E1 should be excluded from the sample. With a high velocity in the opposite direction of the other stars it is equally curious as star E6 in both velocity space and the projected cluster image, where it is somewhat off from the main cluster position. Without star E1 the velocity dispersion of the cluster becomes $\langle v \rangle \simeq 47\text{--}50 \text{ km s}^{-1}$, which results in a estimated mass of about $5100\text{--}5800 M_\odot$.

These estimates for the total cluster mass are upper limits for the estimated mass of the dark point mass in the cluster center. If the cluster potential is dominated by a point mass object with a total mass exceeding the stellar mass by a sizeable fraction, the stars are in orbit around this mass point. In that case some of the stars may be near the pericenter of their orbit. Since the velocity of a star at pericenter will be a factor of $\sim \sqrt{2}$ larger than the velocity in a circular orbit, the estimated black hole mass may therefore also be smaller by up to a factor of 2.

We stress that the IMBH mass will be smaller than the total mass derived above, since the cluster is made up out of the visible stars, unseen lower mass stars, possible stellar remnants, and the potential IMBH. With $300 M_\odot$ (seen) but possibly up to $\sim 1000 M_\odot$ of luminous material, the mass for the IMBH is then reduced to $2000\text{--}5000 M_\odot$. This is much more than the observed mass of the association, providing a lower limit on its dark mass component.

7.1. Simulating IRS 13E

With a present density of $\sim 4 \times 10^8 M_\odot \text{ pc}^{-3}$, a collision runaway in IRS 13E is inevitable, regardless of the nature of the dark material in the cluster (Portegies Zwart et al. 1999; Gürkan et al.

2004; Freitag et al. 2005a, 2005b). Therefore, even if the cluster currently does not contain an IMBH, a collision runaway cannot be prevented if the stars are bound. We have tested this using N -body simulations of small clusters of 256 and 1024 stars, with masses drawn from a Salpeter mass function between 1 and $100 M_\odot$. These clusters, with $W_0 = 6\text{--}9$ King model initial density profiles, exactly filled their Jacobi surfaces and moved in circular orbits at 0.18 pc from the Galactic center. We continued the calculations until the clusters dissolved. These simulations lost mass linearly in time, with a half-mass lifetime of a few $10,000 \text{ yr}$, irrespective of the initial density profile. This is consistent with the results of independent symplectic N -body simulations (Levin et al. 2005). In each of these simulations a minor runaway merger occurred among roughly a dozen stars, creating runaways of $\lesssim 250 M_\odot$. In another set of larger simulations with $1024\text{--}16,386$ stars, the runaway mergers were more extreme, with collision rates exceeding one per century!

We draw two conclusions from these simulations. If the unseen material in IRS 13E consists of normal stars, then (1) the cluster cannot survive for more than a few $\times 10^4 \text{ yr}$, and (2) runaway merging is overwhelmingly likely. If IRS 13E is bound, a cluster of normal stars cannot be hidden within it, and the dark material must ultimately take the form of an IMBH of about $2000\text{--}5000 M_\odot$ (see also Maillard et al. 2004; Schödel et al. 2005).

Thus, we argue that the properties of the dark-matter problem in IRS 13E could be solved by the presence of a single IMBH of mass $\sim 1000\text{--}5000 M_\odot$, consistent with earlier discussions (Maillard et al. 2004; Schödel et al. 2005). In that case the seven observed stars may be the remnant of a larger star cluster that has undergone runaway merging, forming the IMBH during core collapse while sinking toward the Galactic center (Ebisuzaki et al. 2001; Portegies Zwart et al. 2003; Gürkan & Rasio 2005). According to this scenario, the stars we see are the survivors that have avoided collision and remained in tight orbits around the IMBH.

Extensive position determinations with the National Radio Astronomy Observatory’s Very Long Baseline Array (VLBA) of Sgr A* over an $\sim 8 \text{ yr}$ baseline has revealed that the SMBH in the Galactic center (assuming $4 \text{ million } M_\odot$ and a distance of 8.0 kpc) is about $7.6 \pm 0.7 \text{ km s}^{-1}$ (Reid & Brunthaler 2004). An IMBH of $2000\text{--}5000 M_\odot$ orbiting at a distance of $\sim 0.18 \text{ pc}$ would create the linear velocity of about $0.15\text{--}0.39 \text{ km s}^{-1}$ for Sgr A*, since the orbital velocity of IMBH is $\sim 310 \text{ km s}^{-1}$ and its mass is $\lesssim 1/800$ of the central BH, assuming a circular orbit. If observations with the VLBA continue with the same accuracy for the next decade, the IMBH in IRS 13E can be detected by measuring the motion of Sgr A*.

7.2. X-Ray and Radio Observations of the Galactic Center

X-ray observations may offer a better chance of observing an individual IMBH near the Galactic center than the VLBA radio observations discussed in the previous section. Among the ~ 2000 X-ray point sources within 23 pc of the Galactic center (Muno et al. 2003), the source CXOGC J174540.0–290031 (Muno et al. 2004), with $L_{2\text{--}8 \text{ keV}} \simeq 8.5 \times 10^{34} \text{ ergs s}^{-1}$ at a projected galactocentric distance of 0.11 pc , is of particular interest. The peak radio intensity of this source is 0.1 Jy at 1 GHz (Bower et al. 2005), which corresponds to $L_r \sim 8 \times 10^{30} \text{ ergs s}^{-1}$ at the distance of the Galactic center. Using the recently proposed empirical relation between X-ray luminosity, radio flux, and the mass of the accreting black hole (Merloni et al. 2003),

$$\log L_r = 7.3 + 0.6 \log L_X + 0.8 \log M_{\text{bh}}, \quad (5)$$

we derive a black hole mass of about $2000 M_\odot$.

Interestingly, this source has an 7.8 hr periodicity (Muno et al. 2004), which, if it reflects the orbital period, would indicate a semimajor axis of $\sim 25 R_{\odot}$. The companion to the IMBH would then have a Roche radius of $\sim 1 R_{\odot}$, consistent with a $1 M_{\odot}$ main-sequence star. Mass transfer in such a binary would be driven mainly by the emission of gravitational waves at a rate of $\sim 0.01 M_{\odot} \text{ Myr}^{-1}$ (Portegies Zwart et al. 2004b), which is sufficient to power an X-ray transient with the observed X-ray luminosity and a duty cycle on the order of a few percent (Portegies Zwart et al. 2004b).

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